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Impact of furnishing on room airflows

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SUMMARY:
In building simulation it is common to use idealized empty rooms for simulation. However, furnishing elements may cause local microclimates. These microclimates can be critical for instance if furniture is placed close to poorly insulated external walls in Nordic countries, where the external temperatures in the winter season may lead to condensation or high relative humidity on the internal side of the building envelope. Therefore it was important to investigate the influence of furniture on the airflow patterns in rooms and on the local airflow behind the furniture. The current paper presents an investigation of the airflow patterns behind a piece of furniture placed near a cold external wall. The investigation is based on a combination of Particle Image Velocimetry experiments and Computational Fluid Dynamics. The main topic of the investigation is to highlight the effect of increasing the distance between the wall and the furniture as well as between the wall and the floor. As expected the results showed that increased gap widths give increased airflow rates. Comparison of measurements and simulations indicated a good predictability for the cases, where radiation played a minor role.

1. Introduction

1.1 Background

Moisture interactions between room air and surrounding constructions and furniture have a great influence on the indoor environment. High moisture production or cold areas can cause high relative humidity, which can lead to mould growth. This is unwanted in the indoor environment due to concern for the indoor air quality. A review study of humidity in dwellings has been performed by Bornehag et al. (2001) and their advice is to avoid moist buildings. Typically, the critical areas in dwellings occur in insufficient ventilated bedrooms in microclimates behind furniture placed next to exterior walls with poor insulation, The surface temperature of the exterior wall is typically 5-8 °C colder than the room temperature in dwellings with problems. It is assumed that the furniture limits the airflow near the wall and the lack of warm room air near the surface will decrease the surface temperature even more, which can cause problems. When this is combined with a high moisture production rate from sleeping persons during night, the lower temperature in the microclimate causes increased relative humidity and the outcome can be biological growth. However, to be able to quantify the effect of such a microclimate on the indoor environment, there is a lack of knowledge about the airflow velocities behind furniture in dwellings.

Conventional building energy simulations tools can calculate temperatures in walls whereas the room air is represented by just one node. For overall energy performance this simplification is reasonable but for microclimatic investigations more details are needed. The local airflow patterns will influence the microclimate due to changes in the surface heat transfer coefficient and temperature differences. Computational fluid dynamics (CFD) solves the Navier-Stokes equations, which provides both global and local airflow patterns. Many earlier investigations of airflows in rooms have been done with CFD (Nielsen 1998; Murakami & Kato1989; Gan 1995; Teodosiu et al. 2003; Kuznik et al. 2007). The CFD technique is widely used, but the reliability of obtained quantitative information obtained from CFD remains difficult to determine. Therefore experimental validation is usually required.

Several people have used CFD numerical simulation of airflow pattern in full scale rooms and compared them to measured PIV data (Zhao et al. 2001; Sun et al. 2004, Posner et al. 2003). However, Posner used a scaled model for the PIV measurements. Also, numerous studies of airflow patterns in indoor environments have been performed, but in most cases the rooms are idealized empty rooms. Therefore, in the current investigation the room contained a piece of furniture. An earlier investigation by computational fluid dynamics (CFD) showed that different placement of furniture near colder external walls may affect the relative humidities in the microclimate (Mortensen et al., 2007a). In this study the main focus is on the airflow behind the furniture.

1.2 Paper outline

The objective of the present study is to clarify the behaviour of natural convection in microclimates between an external wall and furniture with special focus on airflow patterns and velocities. The natural convection behind furniture in dwellings was investigated by different cases of distance between the furniture and the wall in combination with different leg heights of the furniture. The investigation was performed with a commercial CFD code (Fluent, 2003) and the simulation results were compared to PIV measurements of the same cases.

The PIV measurements of the different cases provide 2D images of the airflow in a few given positions. The numerical 3D model of the room provides a clearer view on the natural convection in the entire test room. The idea was that the numerical simulation could help understand the measurements better since this would reveal 3D effects.

2. CFD model

Obstacles in rooms are known to cause turbulence and most room airflows are turbulent. Therefore, a viscous turbulence model is used. The dilemma is to choose the most appropriate turbulence model because a wide selection is available. The simplest and most widely used is the standard k-ε model, or modifications of it like the Realizable or RNG k-ε models. The presented CFD simulations were performed with the Realizable k-ε viscous model for turbulence, which have been found to predict well the airflow velocities in a room (Teodosiu et al. 2003;Kuznik et al. 2007). However, a comparison of 6 turbulence models by Sun et al. (2004) found indications that the RNG k-ε model would generally be preferred for airflow in full-scale rooms, but also their investigation showed good results with the Realizable k-ε model, and therefore it was used in the current study. The advantage of the Realizable k-ε model proposed by Shih et al. (1995) is that the model satisfies some constraints on Reynolds stresses that are consistent with physics of turbulent flows, which is neither the case for the standard k-ε model nor the RNG k-ε model. The turbulence model was used in combination with enhanced wall treatment.

The enhanced wall treatment is a near-wall modelling method that combines a two-layer model with enhanced wall functions. When the near-wall mesh is fine enough (typically y+ ~1, $y+ \equiv \rho \cdot u_T \cdot y/\mu$, ρ is density, u_T is friction velocity, y is distance to wall and μ is fluid viscosity) the laminar sublayer will be resolved by the traditional two-layer zonal model. However, the enhanced wall treatment does not require all walls to have fine meshes because a blending function combines the viscosity affected region with the outer region (Fluent 2003). Kuznik et al. (2007) found that better flow predictions are obtained when the k-ε model is combined with a two-layer near-wall treatment.

The main focus of the present investigation concerns natural convection caused by buoyancy effects in the air gap near the chilled wall. Therefore the simulations were performed using the Boussinesq approximation, which is given in Equation 1.

$$\rho = \rho_0 \left(1 - \beta \cdot \Delta T\right) \qquad (1)$$

where ρ is the actual density at a given position, ρ_0 is the operating density, β is the thermal expansion coefficient and ΔT is the temperature difference between the actual temperature and the operating temperature.

When the density changes are small, the approximation in Equation 1 is accurate enough.

3. PIV measurements

The Particle Image Velocimetry (PIV) measurements provided 2D velocity vector fields of the flow in the air gap behind the furniture.

3.1 Test Room

A test room was set-up for PIV-measurements on furniture near a colder external wall. An ordinary room with internal dimensions of 3.6 x 4.5 x 2.5 m^3 was created inside a larger test facility. A chilled internal wall was built in the chamber, and a plexiglass box was positioned against that wall to imitate a cupboard placed next to an external wall in a real building. The plexiglass box was used because it provides the transparency that is needed in PIV measurements. An air gap behind the plexiglass furniture allows room air to pass over the chilled surface, and this imitates the microclimates found in ordinary dwellings, see Figure 1. The dimensions of the furniture were 1.5 x 0.46 x 2.0 m^3 (width x depth x height).The set-up of the test room can be seen in Figure 2. Further details of the experimental set-up can be found in Mortensen et al. (2007b).

3.2 PIV Equipment

The two-dimensional flow field was measured by using a smoke of small oil droplets (glycol 0.1 – 1.0μm) as tracers and their motion was captured by a CCD camera (Dantec HiSense camera, 1024 x 1280 pixels). The tracer particles were illuminated by a light sheet of (about 3 mm in thickness) discharged from a water cooled double pulse Nd:YAG laser system (100 mJ/pulse).

An external processor unit triggers signals to the camera and the laser, and coordinates the transportation of data from the camera to the computer processor. Further description of the equipment and measurements can be found in Mortensen et al. (2007b).

4. Description of cases

The purpose of the investigation was to gain information about the airflow distribution patterns in small air gaps between cold exterior walls and furniture placed near it. Figure 1 shows a picture and a perspective projection of the experimental set-up, the same geometry was studied by numerical simulation.

The study involved 2 different distances between the furniture and the wall in combination with 4 different distances between the furniture and the floor. In one of these the furniture is placed directly on the floor. The surface temperature of the chilled wall behind the furniture was constantly 16°C. During the measurements the average room temperature was 22°C (giving a temperature difference of 6°C) but in the numerical simulation the air temperature was slightly smaller, 21.2°C. This lower temperature was caused by the chilled wall together with the temperatures of the other surfaces of the room that were set to 22°C. Table 1 gives the different cases and their distances between the furniture and floor or chilled wall. The absolute camera and laser positions are described in Table 2 and illustrated in Figure 2. Position F is used to compare simulations and measurements.

4.1 Simulations

The simulation model has the same geometry as the measurements.The discretization of the computational domain was accomplished with an unstructured mesh consisting of tetrahedral elements. The advantage of the unstructured mesh is that it can easily be refined in specified areas without addition of unnecessary cells in other parts. This advantage was used in the air gap between the furniture and the wall to obtain a better resolution of the obtained flow velocities. However, the unstructured mesh can cause problems near the walls and this is compensated for by use of the so-called enhanced wall treatment (Teodosiu et al., 2003).

The simulations were split in two parts; first simulations were performed with a rough grid (~400,000 cells) for the entire room to resolve the overall flow pattern, then adaptation of the grid was added in the air gap behind the furniture (>1,100,000 cells) and further iterations were performed to resolve the airflow velocities in the air gap. Even further adaptation was made in the area of the measuring positions to ensure $y+\sim 1$.

The simulations focused only on the airflow in the room so energy and viscous airflow models were used. In the material database, the air properties were set as dry air at 22°C and a boussinesq density. The cold wall was set to 16°C and the other walls 22°C except the gypsum board wall that extends the chilled wall to reach the side wall (behind the camera in Figure 2). This wall was assumed adiabatic. The measuring positions A-G of the PIV equipment are given in Table 2. Here only results from position F will be compared for different furniture position cases (see Table 1).

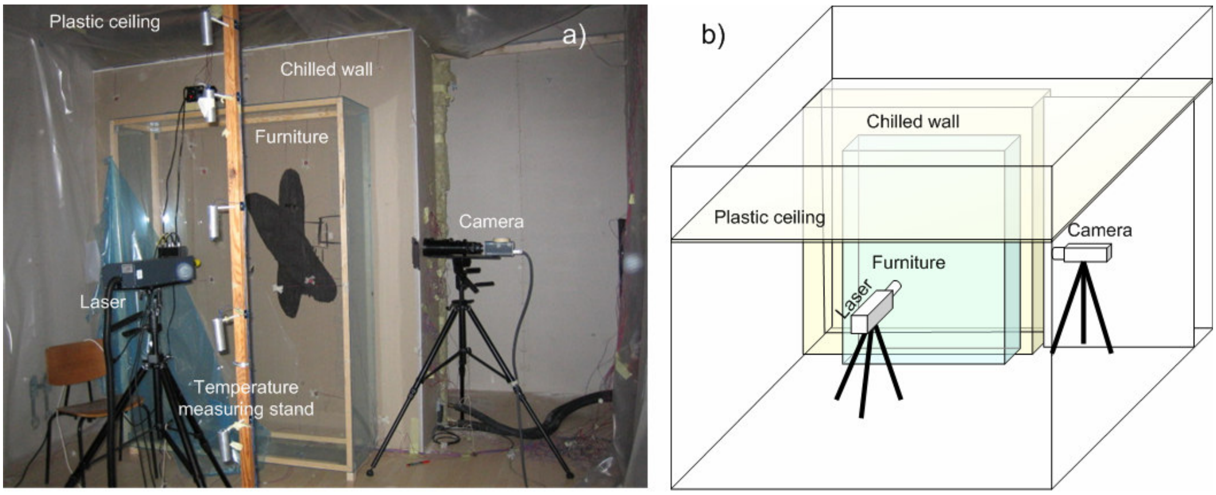

FIG. 1: The experimental set-up, where the camera points into the air gap between the chilled wall and the furniture and the laser sheet is pointed in through the plexiglass furniture. a) A picture of the experimental set-up. b) A diagram of the PIV set-up.

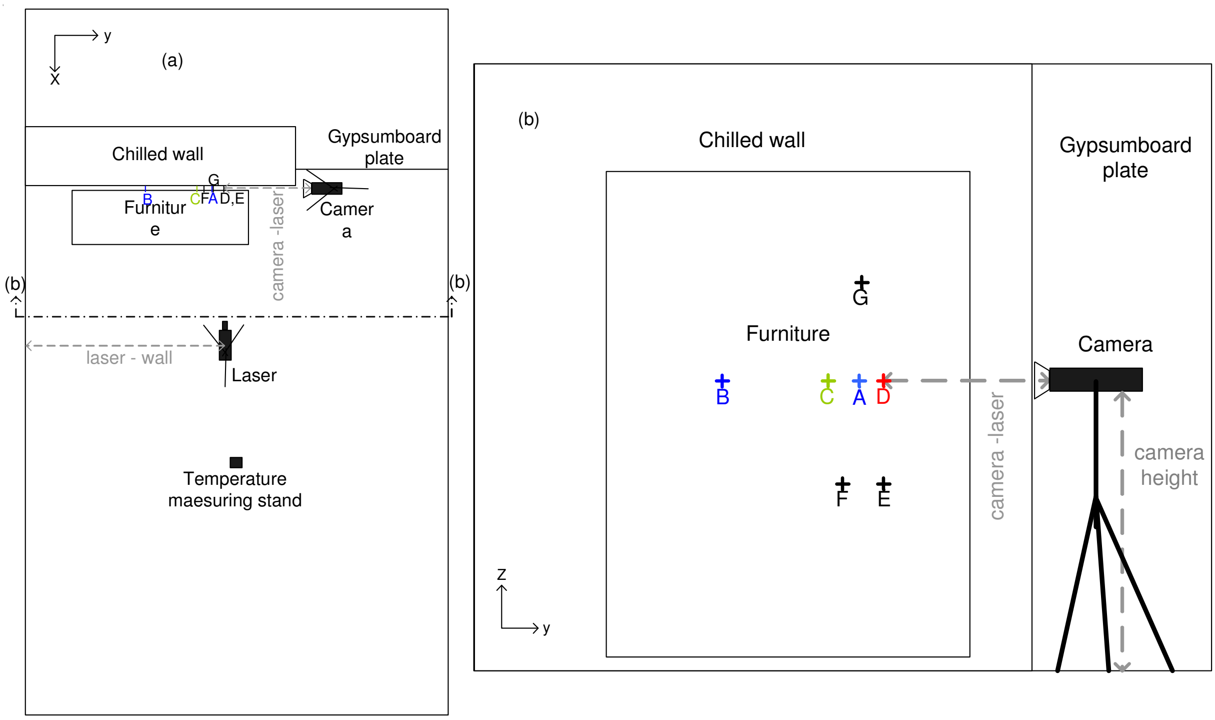

FIG. 2: Part (a) show a plane of the measured PIV set-up and (b) show a front view of the room. The letters A-F show the measuring positions given in table 2.

TABLE 1: The different tested positions of the furniture.

Furniture position	Gap (mm) furniture - floor	Gap (mm) furniture - chilled wall
1	0	25
2	0	50
3	50	25
4	50	50
5	100	25
6	100	50
7	200	25
8	200	50

TABLE 2: Description of PIV measuring positions. The physical image size changes with distance between camera and laser. Only image widths of maximum 50mm is used; the rest is masked out.

Posi-tion	Distance (mm) camera - laser	Image height (mm)	Camera height (mm)	Laser height (mm)	Distance (mm) laser – wall	Measured furniture position
A	1050	124	1183	1192	1570	1-8
B	1420	187	1183	1192	1000	3-4
C	1200	136	1183	1192	1440	3-6
D	920	106	1183	1192	1670	1-8
E	930	113	770	760	1670	3-4
F	1080	130	770	760	1500	1-8
G	970	119	1595	1570	1580	4

5. Results

Only the vertical velocities in the vertical air gap will be shown and discussed, since the horizontal velocities are very small. The horizontal velocities (x-direction in Fig. 2) are in the order of magnitude of 2 % of the vertical velocities in the air gap between the furniture and the chilled wall. The velocity field is set to be positive upwards (z-direction in Fig. 2). In the current paper, PIV measurements results will be presented in form of comparison to numerical simulations.

5.1 Simulation Results for the Entire Room

Figure 3 illustrate the airflow pattern of the room. The highest airflow velocities are seen in the air gap behind the furniture and the velocities behind the furniture increases all the way to the bottom of the air gap.

5.2 Comparison of measurements with CFD

In Figure 4 a comparison is shown between the PIV-measurements and the numerical simulation of the airflow in a gap between the chilled wall and the furniture. The average velocity is calculated and shown in the legend. The figure shows that the shape of the velocity profile is the same for the cases with different distance to the floor but at different velocity levels. However, the shape of the velocity profile changes when the gap is increased from 25 mm to 50 mm. The comparison of the simulation results and the measured data shows that the general shape of the velocity profiles is fairly well predicted by the simulation. The simulated velocities are about half of the measured values for the 25 mm air gap. Opposite to this, the velocity levels are predicted quite well for the cases with a 50 mm air gap, except for the case where the furniture is placed on the floor. The calculated average velocities confirm that the simulation underestimates the velocities. The model predicts the velocities for the 50 mm air gap very accurately but there are some minor differences. For instance, the maximum velocity is underestimated since the measurements found the maximum velocities near the chilled wall at x ~ 40 mm, whereas the simulation have maximum at x~35 mm.

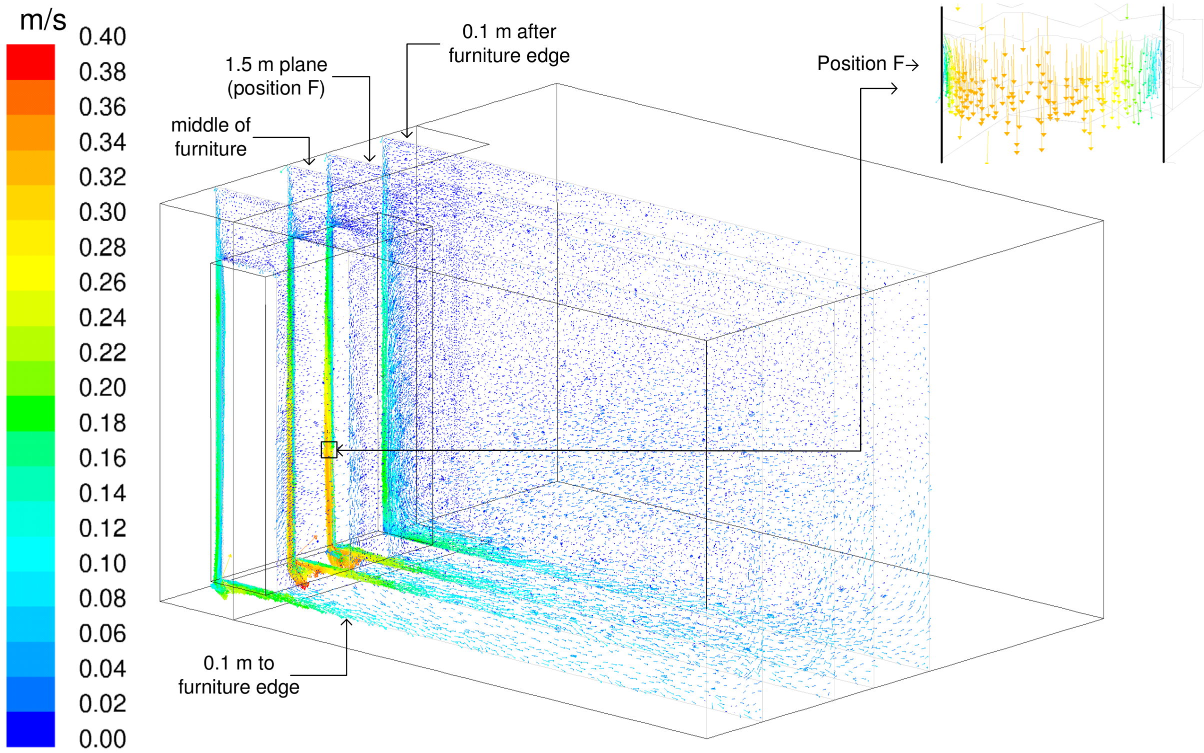

FIG. 3: Airflow patterns are presented as vectors in 3 planes.

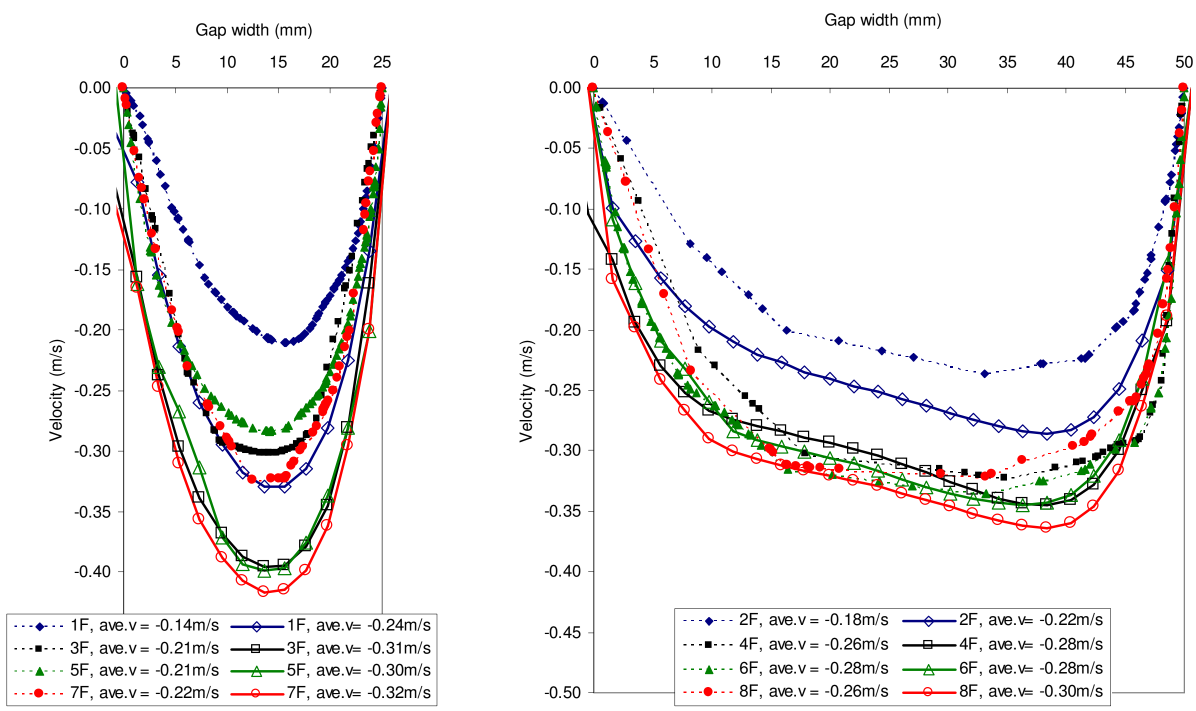

FIG. 4: Comparison of measured (solid) and simulated (dashed) results for position F for a gap width of 25mm and 50mm, furniture surface at x = 0 mm. In the legend the calculated average velocity is given.

6. Discussion

The objective of the current study was to investigate the natural convection between furniture and an exterior wall. The measured data have been compared to simulated data for a similar geometrical setup. The highest airflow velocities in the room are found in the air gap behind the furniture as seen in Figure 3. Two gap widths of 25 and 50 mm have been investigated. The highest measured and simulated velocities were found closest to the chilled wall, see Figure 4. This confirms that density changes dominate the flow by air-cooling in the gap. Both simulations and measurements also confirm that elevation of the furniture will increase the flow behind the furniture. Whether the effect will be enough to avoid problems with condensation or humidity levels suitable for mould growth has not been investigated in this study.

In Figure 3 it is clearly seen that the velocities are highest at the bottom of the airgap, which is a 3D effect as air must have entered from the sides of the furniture. This effect was actually confirmed by the PIV measurements in the other measuring positions as shown in Mortensen et al. (2007b).

In Figure 4 it is seen that the predicted shape of the velocity profiles seem similar to the measured. Especially the simulation results for the 50 mm air gap match the measured data very well. This clearly indicates that CFD simulations can be used to predict airflow velocities in microclimates. However, the model underestimates the velocities in the narrower 25 mm air gap. The profile is predicted well but the velocity level is only about half the measured value. This may be explained by influence of radiation between the surfaces of the wall and furniture, which was not included in these simulations. The velocity of the airflow in the gap is very temperature dependent as the denser cold air will fall towards the floor. This can explain why the narrow gap is highly underestimated as radiation between the surfaces of the chilled wall and the furniture surface may be more pronounced for the 25 mm gap than for the wider 50 mm gap where the distance between the surfaces are twice as wide. For the 50 mm air gap a preliminary test with radiation showed that it had little influence on the results, and since the radiation model cannot be used in Fluent in combination with mesh adaptations, no radiation model was used in the simulations. This implies that for narrow air gaps, initial simulations must be performed in order to investigate what is the influence of radiation, and only if the influence is neglible, the unstructured mesh combined with adaptations can be used to zoom in on a small microclimate.

The good results of the comparison between the simulated and measured data suggest that CFD simulation can be used to accurately calculate the surface heat transfer coefficient which again can be used to predict the water vapour surface resistance. Therefore, this implies that the CFD simulation can be a useful tool for investigation of hygrothermal microclimates in dwellings. However, one should be cautious when radiation plays an import role in the heat transfer in the microclimate, because this might influence the simulated airflow velocities.

This investigation has shown that further analysis should be made where the CFD simulations include radiation in order to see what effect it will have on the prediceted airflow velocities in the air gap.

The starting point for this investigation was the moisture interactions in rooms and particularly the relative humidity in microclimates. However, it is not expected that the airflow velocities in the gap behind the furniture will be affected by moisture in the air as the moisture driven convection potential is much smaller than the buoyancy driven convection. Even though the airflow velocity is properly not influenced by moisture in the air there may still be RH variations behind the furniture compared to the general average in the room as shown in Mortensen et al. (2007a). The narrow air gap has higher airflow velocities but the total volume flow rate is smaller than for the wider 50 mm gap, so less moisture can be transported away from the air gap and a lower airtemperature generally gives higher RH, which may be critical.

7. Conclusion

An investigation was performed using PIV and CFD of the airflow pattern in a small air gap between a chilled wall imitating an exterior wall and a piece of furniture placed next to it. The two investigated gap widths of 25 and 50 mm showed different patterns of velocities but they both seem to be dominated by the boundary flow near the chilled wall, since the maximum velocity was found closest to this wall. The study also confirms that the airflow behind the furniture will increase if the furniture is elevated from the floor.

For a 50 mm air gap the simulated and measured results were rather uniform, which indicates that CFD models can be used to predict airflow velocities in local microclimates. However, the differences between the measurements and the simulations of the narrow 25 mm gap cannot be fully accounted for.

8. Acknowledgements

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